ON THE BURNING OF SINGLE DROPS OF MONOPROPELLANTS

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ABSTRACT

A simplified theoretical treatment has been developed for the burning of single drops of monopropellants. Evaporation constants and the ratios of flame to droplet radii have been calculated for the following monopropellants burning in an inert atmosphere: hydrogen peroxide, nitromethane, hydrazine, ethylene oxide, ozone and nitrous oxide. Compared with the results of similar calculations for fuels burning in air, much smaller flame radii were obtained, while the evaporation constants were found to fall in the same range as before.

Attempts at burning single droplets of monopropellants (e.g. hydrazine and nitromethane) in a nitrogen atmosphere were unsuccessful. Monopropellant droplets burning stably in air were found to extinguish if the oxygen was removed during burning. These experimental findings probably reflect the well-known difficulties encountered in monopropellant operation, which is usually successful only if a suitable reaction catalyst is available. The applicability of calculated monopropellant burning rates to practical cases cannot be assessed at this time.

Single droplets of hydrazine and nitromethane were burnt in air and evaporation constants determined experimentally. The measured rate for nitromethane was found to be in good agreement with calculated results for heterogeneous burning of fuel droplets in air. The measured rate for hydrazine was found to be considerably higher than the value calculated for fuel droplets burning in air or for monopropellant droplets burning in an inert atmosphere. This latter result probably indicates that the assumption of a diffusion flame for the burning of hydrazine in air is not valid, i.e., the hydrazine decomposes throughout the region between the liquid surface and the "flame surface" rather than reacting instantaneously

at the "flame surface".

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NOMENCLATURE

r	radial distance from center of drop
r_ℓ	radius of monopropellant drop
r_c	radius of combustion surface
T_0	temperature of ambient gas
T^*	standard reference temperature (298.16°K)
T_ℓ	normal boiling point of monopropellant
T_c	temperature at combustion surface
T_f	adiabatic flame temperature
t	time
ρ_ℓ	density of liquid monopropellant
$(c_p)_\mu$	specific heat at constant pressure of monopropellant vapor
$(\overline{c_p})_P$	specific heat at constant pressure of reaction products
c_ℓ	specific heat of liquid monopropellant
λ	thermal conductivity
Δ_ℓ	specific latent heat of vaporization of monopropellant
D_K	binary diffusion coefficient for species K
Y_K	weight fraction of species K in gaseous mixtures
$(h_K)_T$	specific enthalpy of species K at temperature T
$\dot{m}_F$	mass rate of flow of monopropellant vapor
a, b	constants in the expression $(c_p)_\mu = a + bT$
$\alpha, \eta, \varphi, \epsilon$	computational parameters
K'	evaporation constant

I. INTRODUCTION

In recent years there has been increased effort to determine the mechanism of combustion of individual droplets of fuel. These basic studies were initiated in order to aid in the design of efficient spray injection type burners.

Most of the previously published experimental work of heterogeneous burning of single droplets has been limited to the study of liquid fuel droplets burning in an oxidizing atmosphere. For example, Godsave (1,2), Goldsmith and Perkins (3), and others have conducted experiments with such hydrocarbon fuels as benzene, ethyl alcohol and n-heptane using air as the oxidizing medium. These investigators have found that for steady burning the square of the burning droplet diameter decreases linearly with time.

Hall and Diederichsen (4) have carried out experimental studies on the combustion of drops of liquid fuels at various pressures. They concluded that the mass rate of burning of fuel droplets is roughly proportional to the one-fourth power of the pressure for pressures up to twenty atmospheres.

Efforts have also been made towards understanding the mechanism of burning of single drops of fuel in oxidizing atmospheres. Godsave (1,2) obtained a useful theoretical interpretation of his experimental results by assuming that the chemical reaction rates do not control the rate of burning. Under these conditions the problem is essentially a study of heat and mass transfer between the flame front, the fuel droplet, and the surrounding atmosphere. The location of the reaction front is determined empirically. With this physical model Godsave derived an explicit expression for the burning rate of liquid fuel droplets which contained two adjustable parameters. These were the temperature of the flame front and the combustion radius. Godsave (1,2) showed that the use of reasonable values

for these parameters was consistent with the observed mass burning rates.

Goldsmith and Penner (5) and Graves (6) obtained explicit relations for the mass burning rates of fuel droplets by postulating that the position of the flame front is established in such a way that the delivery rates of fuel to oxidizer are in stoichiometric proportions. These authors derived relations for the radius of the flame front, the flame temperature, and the mass flow rate, which contained no adjustable parameters.

The method of Goldsmith and Penner can be extended to calculations of burning rates for monopropellants. It is the purpose of the present study to show the required modifications for monopropellants in the special case in which chemical reaction rates are not rate-controlling.

The assumed mechanism for the combustion processes is the following. The fuel evaporates and diffuses to the reaction front, which is assumed to be a spherical shell surrounding the droplet. The location of the reaction front is defined by assuming that the reaction zone temperature is 0.90 of the adiabatic flame temperature. It is assumed that the reactants are consumed instantaneously upon reaching the flame front. The problem of determining the rate of burning, therefore, requires solving a transport problem. Generally the rates of mass and heat transfer will be increased by the effects of convection. Therefore, a lower limit for the burning rate will be obtained if the analysis is made for a droplet burning in a still atmosphere, neglecting the convection of hot gases over the fuel droplet.

A detailed discussion of the theory and a derivation of the basic relations, following closely the paper of Goldsmith and Penner, is given in Section II. The results of representative calculations are described in Section III for the following monopropellants: hydrogen peroxide,

nitromethane, hydrazine, ethylene oxide, ozone, and nitrous oxide, all burning in nitrogen.

Some unsuccessful attempts at igniting single droplets of monopropellants (hydrazine and nitromethane), supported from a quartz fiber in nitrogen, are described in Section IV. These same monopropellants burning stably in air were found to extinguish when the oxygen was removed from the surrounding atmosphere. These results probably reflect the well-known practical difficulties encountered in monopropellant operation, which is often successful only if suitable ignition catalysts are employed.

The evaporation constants for the burning of hydrazine and nitromethane in air were determined experimentally. In Section V these experiments are described, and a comparison is made with results calculated for the heterogeneous burning of fuel droplets in air.

II. A SIMPLIFIED MODEL FOR THE BURNING OF SINGLE DROPS OF MONOPROPELLANT*

In order to present a clear picture of the physical model upon which the analysis is based, the important assumptions are listed in detail below: 1. The droplets are spherical. 2. Convection effects may be neglected. 3. The flame front surrounding the drop is represented by a spherical surface concentric with the drop. All reactions take place instantaneously at this surface, at which the temperature is assumed to be 0.90 of the adiabatic flame temperature. The calculated burning rates are not a sensitive function of the assumed ratio of flame surface temperature to adiabatic flame temperature. 4. Steady state solutions are assumed for fixed droplet sizes. 5. The effect of heat transfer by radiation is neglected. 6. Mean values are used, when appropriate, for the physical properties. 7. The temperature of the monopropellant drop is assumed to be uniform and equal to the boiling temperature. Although this assumption is questionable, it does not exert a large effect on the theoretical results. 8. The pressure is assumed to be uniform throughout the system.

A schematic diagram of an evaporating and burning monopropellant droplet in an inert atmosphere is shown in Fig. 1. The radius of the liquid drop is r_ℓ and its temperature is the normal boiling point T_ℓ. The radial distance of the combustion surface from the center of the liquid droplet is r_c and its temperature, T_c, is 0.90 of the adiabatic flame temperature T_f, i.e. $T_c = 0.9\ T_f$. The inert gas mixture at a large distance from the combustion surface is at temperature T_0.

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* The present discussion follows closely the wording in the paper by Goldsmith and Penner (5). However, appropriate changes are introduced whenever necessary in order to make the analysis applicable for our model of monopropellant burning.

Let $\dot{m}_F$ represent the steady-state mass rate of fuel consumption, which is the desired eigenvalue of the boundary-value problem; t is the time, ρ, c_p and λ represent, respectively, the density, specific heat at constant pressure, and thermal conductivity; Δl equals the specific latent heat of evaporation of the fuel.

For a constant-pressure flow process, the first law of thermodynamics leads to the relation

$$\frac{dh}{dt} = \frac{dq}{dt}$$

where dh/dt is the rate of enthalpy increase of the gases passing through a fixed volume to which the total rate of energy transfer is dq/dt. For a spherical shell bounded by the radii r_i and r_f, the energy equation takes the form

$$\dot{m}_F\left[(h_\mu)_f - (h_\mu)_i\right] = -\left\{\left[4\pi r^2 \lambda \frac{dT}{dr}\right]_i - \left[4\pi r^2 \lambda \frac{dT}{dr}\right]_f\right\} \tag{1}$$

where the subscripts i and f identify, respectively, the surfaces at r_i and r_f, and h_μ is the specific enthalpy of the monopropellant.

The general continuity equation for species K can be written in the form

$$\dot{m}_K = 4\pi r^2 \rho Y_K\left[\frac{\dot{m}_F}{4\pi r^2 \rho} - \frac{D_K}{Y_K}\frac{dY_K}{dr}\right] \tag{2}$$

where $\dot{m}_K$ is the rate of mass transport of species K, ρ is the density of the gas mixture. Y_K equals the weight fraction of the species K, and D_K is the appropriate diffusion coefficient for species K. Equation (2) states that the total mass transport of species K is equal to the sum of the mass transport of species K associated with the movement of the average fluid, Y_K $\dot{m}_F$, and with the mass transfer by diffusion, $-4\pi r^2 \rho D_K \frac{dY_K}{dr}$.

The momentum equation reduces to the statement that the pressure is practically constant, which is assumed to be the case in the analysis.

A. Derivation of Godsave's Equation for $\dot{m}_F$.

The expression for conservation of energy, given in Equation (1), is applied to the spherical shell between r_ℓ and r for $r < r_c$. The rate of enthalpy transport at r_ℓ is

$$\dot{m}_F (h_\mu)_{T_\ell}$$

and at r

$$\dot{m}_F (h_\mu)_T$$

The rate of energy transport by thermal conduction at r_ℓ is

$$-\left[4\pi r^2 \lambda \frac{dT}{dr}\right]_{r_\ell} = -\dot{m}_F \Delta\ell$$

and the rate of energy transport at r into the spherical shell between r_ℓ and r is

$$4\pi r^2 \lambda \frac{dT}{dr}$$

Hence Equation (1) becomes

$$\dot{m}_F\left[(h_\mu)_T - (h_\mu)_{T_\ell}\right] = -\dot{m}_F \Delta\ell + 4\pi r^2 \lambda \frac{dT}{dr}$$

or

$$4\pi r^2 \frac{dT}{dr} = \frac{\dot{m}_F}{\lambda}\left[\Delta\ell + \int_{T_\ell}^{T} (c_p)_\mu \, dT\right] \qquad (3)$$

where the subscript μ to the specific heat indicates the monopropellant vapor. If it is assumed that $\lambda = \lambda_1$ is independent of temperature and

also that $(c_p)_u = (\overline{c}_p)_u$ is constant, then Equation (3) becomes

$$4\pi r^2 \frac{dT}{dr} = \left[\frac{\dot m_F (\overline{c}_p)_u}{\lambda_1}\right]\left[\frac{\Delta l}{(\overline{c}_p)_u} + (T - T_l)\right]$$

Integration of the preceding expression between the limits $r = r_l$ at $T = T_l$ and $r = r_c$ at $T = T_c$ leads directly to Godsave's equation for $\dot m_F$, viz.,

$$\dot m_F = \frac{4\pi \lambda_1 r_l \ln\left[1 + \frac{(\overline{c}_p)_u}{\Delta l}(T_c - T_l)\right]}{(\overline{c}_p)_u \left[1 - (r_l/r_c)\right]} \tag{4}$$

Examination of Equation (4) shows that for $r_c >> r_l$, or for constant values of r_l/r_c, $\dot m_F$ is a linear function of the droplet radius. Also, since T_c is generally large compared to T_l, it follows that $\dot m_F$ is not a sensitive function of T_l.

It should be noted that Equation (4) was derived without making any special assumptions about the location of the reaction front. For this reason the expression for $\dot m_F$ contains two unknown parameters, T_c and r_c.

B. An Expression For $\dot m_F$ If λ and $(c_p)_u$ Are Linear Functions of the Temperature.

A refinement of Godsave's equation was obtained by Goldsmith and Penner by deleting the assumptions (a) that λ can be assigned an average value, λ_1, in the temperature interval between T_l and T_c, and (b) that the specific heat of the monopropellant vapor is constant. We use the following approximate expressions:

$$\lambda = \lambda_l \left(\frac{T}{T_l}\right) \tag{5}$$

where λ_l is the thermal conductivity of the monopropellant-inert gas

mixture at the temperature T_ℓ, and

$$(c_p)_u = a + bT \tag{6}$$

where a and b are suitably chosen constants. Equations (3), (5) and (6) lead to the result,

$$4\pi r^2 \frac{dT}{dr} = \frac{\dot{m}_F T_\ell}{\lambda_\ell T}\left[a(T-T_\ell) + \frac{b}{2}(T^2 - T_\ell^2) + \Delta\ell\right]$$

Integration of this expression from r_ℓ, T_ℓ to r_c, T_c results in the relation

$$\dot{m}_F = \frac{4\pi\lambda_\ell r_\ell}{b T_\ell\left(1-\frac{r_\ell}{r_c}\right)}\left\{\ln\left[1 + \frac{(T_c - T_\ell)}{\Delta\ell}\left(a + \frac{b}{2}T_c + \frac{b}{2}T_\ell\right)\right] + \left[\varphi_c - \varphi_\ell\right]\right\} \tag{7}$$

where

$$\varphi = \begin{cases} -\dfrac{2a}{\sqrt{\eta}}\tan^{-1}\dfrac{a+bT}{\sqrt{\eta}} & \text{for } \eta > 0 \\[2ex] \dfrac{2a}{\sqrt{-\eta}}\tanh^{-1}\dfrac{a+bT}{\sqrt{-\eta}} & \text{for } \eta < 0 \end{cases} \tag{8}$$

where φ_c is the value of φ for $T = T_c$ and φ_ℓ is the value of φ for $T = T_\ell$, and

$$\eta = 2b\left(\Delta\ell - \frac{b}{2}T_\ell^2 - aT_\ell\right) - a^2 \tag{8a}$$

Reference to Equations (7) and (8a) shows again that $\dot{m}_F$ is determined provided r_c and T_c are known.

C. Determination of the Combustion Radius.

For the spherical shell between $r > r_c$ and r_c, Equation (1) becomes

$$\dot{m}_F (h_p)_T - \dot{m}_F (h_p)_{T_c} = \left[4\pi r^2 \lambda \frac{dT}{dr}\right]_r - \left[4\pi r^2 \lambda \frac{dT}{dr}\right]_{r_c} \tag{9}$$

where h_p denotes the specific enthalpy of the products of reaction. The term $-\left[4\pi r^2 \lambda \, dT/dr\right]_{r_c}$ equals the total heat evolved on reaction at T_c minus the energy transported to the fuel droplet, i.e.

$$-\left[4\pi r^2 \lambda \frac{dT}{dr}\right]_{r_c} = \dot{m}_F \left\{-(h_p)_{T_c} + (h_\mu)_{T_c} - \Delta_\ell - \left[(h_\mu)_{T_c} - (h_\mu)_{T_\ell}\right]\right\}$$

where h_μ is the specific enthalpy of the monopropellant. Hence Equation (9) becomes

$$-4\pi r^2 \lambda \frac{dT}{dr} = \dot{m}_F \left\{q^* - \left[(h_p)_T - (h_p)_{T^*}\right]\right\} \tag{10}$$

where

$$q^* = -(h_p)_{T^*} + (h_{\mu,\ell})_{T^*} + c_\ell (T_\ell - T^*) \tag{11}$$

Here T^* is a standard reference temperature (298.16°K), and c_ℓ denotes a constant specific heat for the liquid monopropellant in the temperature range T^* to T_ℓ. The quantity q^* differs from the standard heat of combustion for one gram of liquid monopropellant through the addition of the term $c_\ell (T_\ell - T^*)$. If $(\bar{c}_p)_p$ is independent of the temperature, then Equation (10) reduces to the relation

$$-4\pi r^2 \lambda \frac{dT}{dr} = \dot{m}_F \left[q^* - (T - T^*)(\bar{c}_p)_p\right] \tag{10a}$$

This equation is of the form

$$4\pi r^2 \lambda \frac{dT}{dr} = \dot{m}_F (\bar{c}_p)_p (\alpha + T) \tag{10b}$$

with

$$\alpha = -\frac{q^*}{(\bar{c}_p)_p} - T^* = -T_f \tag{12}$$

Replacing λ by $\lambda_c T/T_c$ in Equation (10b) and integrating from r_c, T_c to ∞, T_o the following relation is obtained

$$\frac{1}{r_c} = \frac{4\pi\lambda_c}{\dot{m}_F(\bar{c}_p)_p T_c}\left[(T_o - T_c) + T_f \ln\left(\frac{T_o - T_f}{T_c - T_f}\right)\right] \tag{13}$$

From Equations (7) and (13) an expression for r_c/r_ℓ is obtained, viz.

$$\frac{r_c}{r_\ell} = 1 + \frac{\lambda_\ell T_c (\bar{c}_p)_p \mathcal{E}}{\lambda_c T_\ell\, b}\left[(T_o - T_c) + T_f \ln\left(\frac{T_o - T_f}{T_c - T_f}\right)\right]^{-1} \tag{14}$$

where

$$\mathcal{E} = \ln\left[1 + \left(\frac{T_c - T_\ell}{\Delta_\ell}\right)\left(a + \frac{b}{2}T_c + \frac{b}{2}T_\ell\right)\right] + \left[\varphi_c - \varphi_\ell\right] \tag{15}$$

Reference to Equation (14) shows that r_c/r_ℓ is a constant for fixed values of the physico-chemical parameters. Hence Equation (7) shows that $\dot{m}_F$ is a linear function of r_ℓ.

D. The Evaporation Constant K'.

The linear relation between $\dot{m}_F$ and r_ℓ has been used to obtain the following expression for the variation of droplet diameter with time:

$$d^2 = d_o^2 - K't \tag{16}$$

where d is the droplet diameter at time t, d_o is the initial droplet diameter, and the constant K' is referred to as the evaporation constant. It is easily shown that K' is related to $\dot{m}_F$ through the expression

$$K' = \frac{2\dot{m}_F}{\pi r_l \rho_l} \tag{17}$$

III. RESULTS OF REPRESENTATIVE CALCULATIONS

The procedure for calculating the various quantities involves the following steps:

(a) For suitably chosen values of the physico-chemical parameters and assuming $T_c = 0.90T_\ell$, the computational parameter $\mathcal{E}$ is obtained from Equation (15).

(b) The quantity r_c/r_ℓ is obtained from Equation (14).

(c) $\dot{m}_F/r_\ell$ is determined from Equation (7).

(d) Finally, the evaporation constant, K', is calculated from Equation (17).

The calculations were carried out for the monopropellants decomposing as indicated below:

(a) Hydrogen Peroxide

$$H_2O_{2(\ell)} \longrightarrow H_2O_{(g)} + \tfrac{1}{2}O_{2(g)}$$

(b) Nitromethane

$$CH_3NO_{2(\ell)} \longrightarrow 0.2CO_{2(g)} + 0.8CO_{(g)} + 0.7H_{2(g)} + 0.5N_{2(g)} + 0.8H_2O_{(g)}$$

(c) Hydrazine

$$N_2H_{4(\ell)} \longrightarrow N_{2(g)} + 2H_{2(g)}$$

(d) Ethylene Oxide

$$C_2H_4O_{(\ell)} \longrightarrow CO_{(g)} + CH_{4(g)}$$

(e) Ozone

$$2O_{3(\ell)} \longrightarrow 3O_{2(g)}$$

(f) Nitrous Oxide

$$N_2O_{(l)} \longrightarrow N_{2(g)} + \tfrac{1}{2}O_{2(g)}$$

The appropriate values of the physico-chemical parameters and the calculated values for r_c/r_l and K' are listed in Table I.

TABLE I. PHYSICO-CHEMICAL PARAMETERS AND CALCULATED VALUES FOR r_c/r_ℓ AND K'

Fuel	Hydrogen Peroxide	Nitromethane	Hydrazine	Ethylene Oxide	Ozone	Nitrous Oxide
T_o (°K)	300	300	300	300	300	300
T^* (°K)	298	298	298	298	298	298
T_ℓ (°K)	425	374	387	284	163	186
T_c (°K)	1125	2200	780	1287	2543	1395
T_f (°K)	1250	2450	867	1430	2825	1550
a (cal/gm-°K)	0.221	0.314	0.317	0.222	0.146	0.186
b (cal/gm-°K^2)	0.124×10^{-3}	0.145×10^{-3}	0.412×10^{-3}	0.425×10^{-3}	0.148×10^{-3}	0.095×10^{-3}
Δ_ℓ (cal/gm)	373	150	312	139	54	90
η (cal/gm-°K)^2	0.0176	-0.0921	0.0200	0.0008	-0.0119	-0.0244
$\mathcal{E}$	0.208	0.620	0.203	0.920	1.340	0.370
$(\bar{c}_p)_p$ (cal/gm-°K)	0.404	0.471	0.667	0.583	0.282	0.274
λ_ℓ (cal/cm-sec-°K)	1×10^{-4}	5×10^{-5}	1×10^{-4}	5×10^{-5}	2×10^{-5}	3×10^{-5}
ρ_ℓ (gm/cm^3)	1.40	0.99	0.93	0.89	1.71	1.23
r_c/r_ℓ	1.415	1.596	1.285	1.640	1.645	1.521
K' (cm^2/sec)	7.70×10^{-3}	12.3×10^{-3}	4.90×10^{-3}	8.80×10^{-3}	13.3×10^{-3}	11.9×10^{-3}

Reference to Table I shows that the calculated values of K' fall in the range 5 to 12 x 10^{-3} cm^2/sec, which is similar to the results obtained for the heterogeneous burning of fuel droplets in air. On the other hand, the calculated values of r_c/r_ℓ are roughly 1.5, which is only about one fourth of the corresponding results for fuel droplets burning in air. It should be noted that observed flame radii for fuels burning in air are generally much smaller than the calculated radii. This result, as well as the impossibly high flame temperatures obtained (neglecting dissociation) for fuels burning in air on the assumption that the flame surface corresponds to the position where the delivery rates of fuel to oxidizer are in stoichiometric proportions, suggests that the assumption $T_c = 0.9T_f$ may be a generally useful concept.

IV. EXPERIMENTAL STUDIES ON IGNITION AND BURNING OF MONOPROPELLANT DROPLETS

A. Burning of Single Drops in a Nitrogen Atmosphere

The apparatus used for the experimental work is shown in Fig. 2. The object of the investigation was to photograph and record the decrease in drop size with time during combustion. The combustion tank shown in Fig. 2 was used so that the monopropellant droplet could be surrounded by nitrogen. The tank had the shape of a cube measuring 12 inches on each side (inside), and was made of 1/2 inch thick lucite except for the 1/4 inch thick front and back panels.

Nitrogen was introduced through a 3/8 inch fitting screwed into the tank side. A similar fitting on the opposite side of the tank, open to the atmosphere, served as an exhaust line.

A fine silica filament was cemented to a brass bolt screwed through the top of the tank. The filament and bolt were of such a length that the tip of the filament was about in the center of the tank. It was necessary to thicken the end of the filament in order to retain the liquid drop on the filament. The diameter of the thickened end was approximately 0.30 mm.

The drops were suspended on the filament by means of a hypodermic syringe and an eight inch needle inserted through a rubber diaphragm in the top of the tank. The drops were between 1.5 and 2.5 mm in diameter. The diaphragm was made by cementing a piece of 1/16 inch neoprene over a 1-1/2 inch hole cut into the top of the tank. A sketch of this operation is shown in Fig. 3. After suspending the drop the needle was withdrawn and the diaphragm sealed itself.

It was planned to ignite the drops by means of an electric spark.

For this purpose electrodes of 1/16 inch brass rod were bolted to the sides of the tank and positioned so as to leave a gap of about 1 cm. across the filament tip.

The first attempts to ignite the drop were made using a six-volt storage battery connected through a spark coil and an on-off switch to the electrodes. Attempts were made to ignite nitromethane and hydrazine by this method but all attempts failed.

The battery and spark coil were then replaced by a continuously sparking Tesla coil leak tester, which was connected to the electrodes. The spark was hot enough to cause rapid evaporation of the drops but would not ignite them. The sparks were observed to "go around" the drop of nitromethane no matter how short the distance between electrode and drop. On the other hand the sparks appeared to "go through" the hydrazine; in this case the only observed effect, besides rapid evaporation, was a yellowish discoloration of the drop.

Believing that more powerful sparks would only succeed in knocking the drop off the filament, it was decided to try ignition by means of a hot wire. For this purpose a probe was built by passing two large insulated copper wires through a 1/4 inch copper tube about 10 inches long.

The ends of this tube were sealed with cement and small pieces of tungsten wire were clipped to one end. The other end was connected to a six volt storage battery. The temperature of the tungsten wire was controlled by its length. Pieces about 1 inch in length or less would burn out almost instantly when the battery was connected. The probe was introduced into the combustion tank by passing it through a 1/8 inch hole cut into the neoprene diaphragm. A sketch of this arrangement is shown in Fig. 4.

Two different hot wire arrangements were used in the ignition attempts. At first a 1 cm. piece of tungsten wire was used and passed through the drop. When the battery was connected, the tungsten burned out with the expected white flash but the drop was undisturbed.

A second attempt was made using a tungsten wire about 2 inches long formed in the shape of a coil. The coil was passed around the drop and the battery connected. The temperature of the wire was increased by using progressively shorter wires. With 1 inch lengths the wire burned out almost instantly. The only effect of increasing the wire temperature was to increase the evaporation rate of the drop. A last attempt was made using a 1-1/4 inch tungsten wire and placing the white hot wire in contact with the drop. The drop evaporated more rapidly than before but did not ignite. Removal of the hot wire after a short time immediately halted the rapid evaporation, thereby eliminating the possibility that the drop was actually burning with an invisible flame.

It was felt that any further attempts to ignite the drops under these conditions would be futile. It was decided to study the change which occurred in a continuously burning drop as an oxidizing atmosphere was replaced by an inert atmosphere.

B. Apparatus for Continuously Burning Drops*

The apparatus used for the experimental work with a continuously burning drop is shown in Fig. 5. The object of the investigation was to photograph and record the change in flame characteristics as an oxidizing atmosphere was gradually replaced with an inert atmosphere. Continuous burning

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* The author is indebted to Mr. M. Goldsmith for the loan of the apparatus used in these studies.

was obtained by feeding the monopropellant through a hypodermic needle with a porous ball cemented to its end. The porous ball was made from alumina and had a diameter of about 7 mm. A small hole was drilled in the ball into which the needle was cemented using a high temperature ceramic cement. The needle was attached to a 50 cc hypodermic syringe held fixed in the apparatus by two clamps. The plunger was moved through reduction gears and a worm drive by a 12 volt, 4,000 rpm D.C. motor, controlled by a rheostat and rectifier. With this arrangement the monopropellant fuel flow could be varied from zero to a level where excess liquid would drop from the porous ball. The needle and ball were introduced into the combustion tank by means of a slotted bolt threaded into the side of the tank.

It was planned to ignite the drop in air and then, after adjusting the rheostat for steady burning, to introduce nitrogen slowly until the tank atmosphere was inert. The burning drop could be photographed with a 35 mm movie camera at intervals during the cycle.

The drop was ignited using the probe and tungsten wire coil. Ignition occurred quite readily. The rheostat was adjusted to maintain continuous burning and nitrogen was slowly introduced into the tank. As the nitrogen entered the flame became very sensitive to any mechanical influence. Jarring the tank or needle would cause the flame to extinguish immediately. Variation in the feed rate would sometimes cause a drop of monopropellant liquid to drop from the porous ball. When this happened the flame would go out. As the burning time and percentage of inert atmosphere increased the sensitivity increased until eventually every drop would be extinguished despite a plentiful supply of monopropellant fuel. Once extinguished the drop could not be ignited until the tank had been flushed with air.

In order to determine whether this phenomenon was due to lack of

oxygen or to mechanical disturbance, the porous ball was removed from the tank and set up as shown in Fig. 6. The drop was ignited and the apparatus adjusted for continuous burning. As long as the drop was burning in air it continued to burn with a steady flame. Vibration or jarring of the needle had no effect on the flame. Increasing the monopropellant mass flow caused excess liquid to drop from the porous ball but with no detrimental effect on the flame. In order to check the effect of lack of oxygen, a 500 cc beaker was inverted over the flame. Within a few seconds the flame exhibited the same type of sensitivity it had in the combustion tank and was easily extinguished by a slight vibration or jarring. When great care was taken to eliminate any mechanical disturbance the flame lasted a short while longer but eventually was extinguished. As a final check, the beaker was flushed with nitrogen and then inverted over the burning drop. The flame was instantly extinguished.

V. EXPERIMENTAL STUDIES ON THE BURNING OF MONOPROPELLANTS IN AIR

Since the nitromethane and hydrazine drops would not burn in an inert atmosphere, at least without a suitable catalyst, it was decided to compare the burning rates in air of these monopropellants with the calculated burning rates for burning of fuel droplets in air.

The apparatus used for this investigation is shown in Fig. 7. The silica filaments were similar to the ones previously described. The drops were suspended on the filament by means of a hypodermic syringe and needle. Ignition was accomplished by a small flame.

An electrically driven Arriflex 35 mm movie camera was used to photograph the burning drops. The drops were photographed in silhouette by providing strong background illumination. A 10 inch adapter tube was used with the lens to obtain as large an image of the drop as possible. A lens setting of f9 was determined to be satisfactory. The background illumination was provided by a 100 watt light bulb located directly behind the filament tip. Kodak Super XX 35 mm film was used.

The drops were photographed at a camera setting of 26 frames per second. The actual camera speed at this setting was checked by photographing a 500 watt light bulb through slots cut into an aluminum disk attached to a constant-speed motor. With this stroboscope the camera timing was found to be 26.31 frames per second (1 frame per 0.0384 seconds).

A 3/32 inch ball bearing was photographed at the beginning of each 100 foot roll of film. This calibration was carried out under the same camera focusing conditions as for the burning drops, thereby providing an accurate reference measurement for determining the magnification of the photographs and, consequently, the actual size of the drops.

The size of the burning drops was determined by using a technique very

similar to that described by Godsave (2). The film was measured with the aid of a 35 mm microfilm reader (to produce further magnification) and a steel scale graduated to 1/2 of a millimeter. Two measurements were made on each frame, namely, the two perpendicular diameters inclined at 45° to the major and minor axes in the plane of observation. The mean of these two measurements was recorded as the "effective diameter" of the drop. If the major and minor axes do not differ greatly, as was the case in these tests, then it is easily shown that the volume of a sphere with the measured effective diameter is not greatly different from that of the prolate spheroid which actually corresponds to the shape of the drop. As can be seen from Fig. 8, the suspended drops were reasonably spherical during the major part of their life.

In most cases, measurements of each drop were taken over a range of sizes extending from the initial to approximately one half of the initial drop diameter. Every fifth frame of the film for each drop was measured.

The experimental results gave directly the drop diameter, d, as a function of time, t. The plots of d^2 against t were found to be linear. Typical experimental plots for nitromethane and hydrazine are shown in Figs. 9 and 10, respectively. The value of K' is determined directly from the slope of the straight lines and has the dimensions cm^2/sec.

The calculated evaporation rates for burning of fuel droplets in air were obtained using the equations derived by Goldsmith and Penner (5). These results are compared with the observed values of K' in Table II.

Reference to Table II shows that the measured burning rate for nitromethane burning in air is in good agreement with calculated results. Comparison with the evaporation constant calculated for nitromethane burning in an inert atmosphere shows the anticipated result, namely, since the

reaction products do not differ greatly, the burning rates are similar.

The value of burning rate observed for hydrazine burning in air was found to be considerably higher than the value calculated for fuel droplets burning in air or for monopropellant droplets burning in an inert atmosphere. This result indicates that the assumption of a simple diffusion flame is probably not valid. It is more probable that the hydrazine decomposes throughout the region between the liquid droplet and the "combustion surface" rather than instantaneously at the "combustion surface".

TABLE II. COMPARISON OF CALCULATED AND OBSERVED VALUES FOR THE EVAPORATION CONSTANT K'

	Hydrazine	Nitromethane
Calculated value in inert atmosphere	0.0049	0.0123
Calculated value in air	0.0087	0.0113
Observed value in air	0.0212	0.0109

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4. A.R. Hall and J. Diederichsen, "An Experimental Study of the Burning of Single Drops of Fuel in Air at Pressures up to Twenty Atmospheres", Fourth (International) Symposium on Combustion, Williams and Wilkins Company, Baltimore 1953, pp. 837-846.

5. M. Goldsmith and S.S. Penner, "On the Burning of Single Drops of Fuel in an Oxidizing Atmosphere", Jet Propulsion, Vol. 24, 1954, pp. 245-251.

6. C.C. Graves and M. Gerstein, "Some Aspects of the Combustion of Liquid Fuel", AGARD Meeting, Scheveningen, May 1954 (in press).

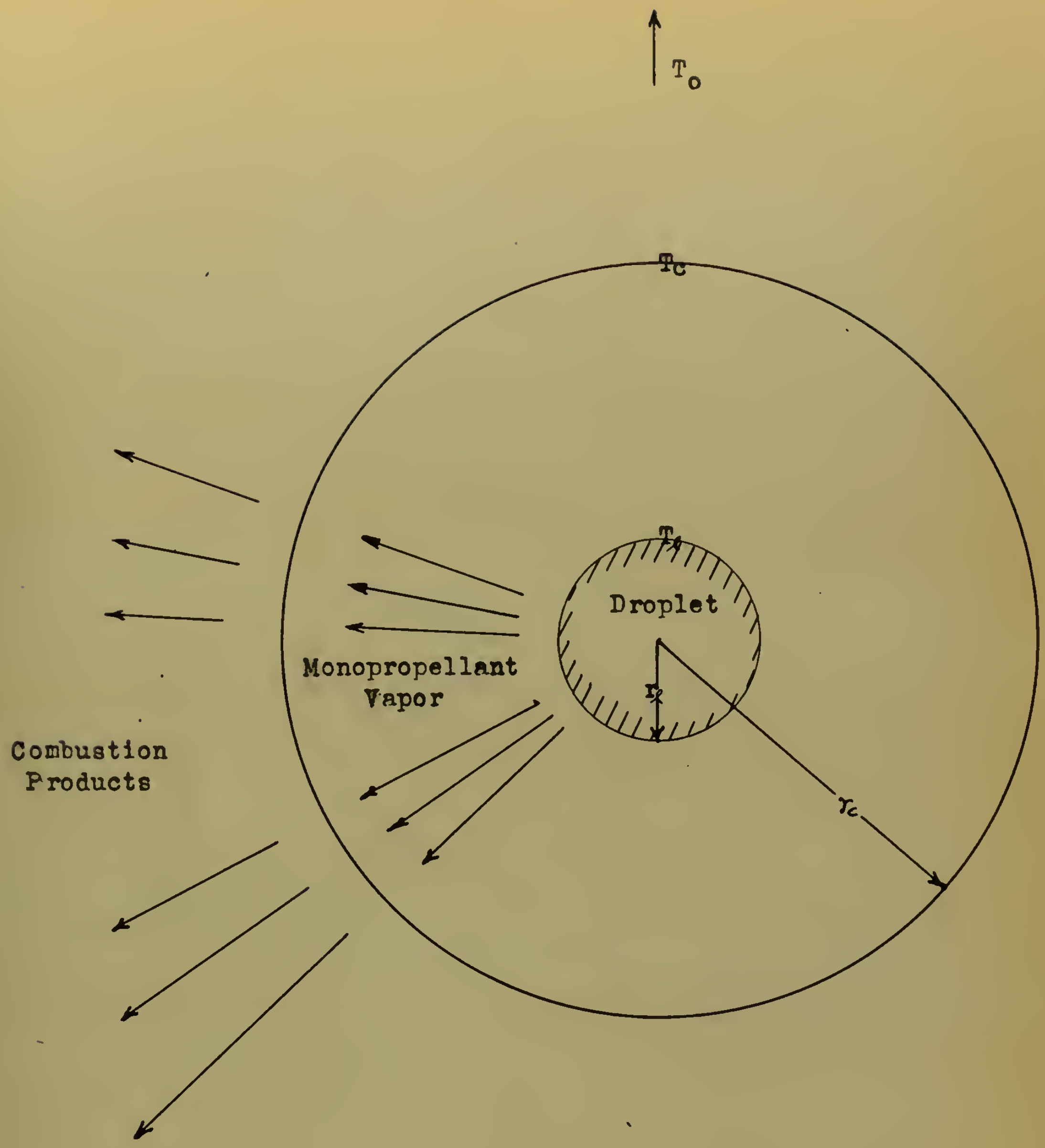


FIGURE 1. SCHEMATIC DIAGRAM OF BURNING MONOPROPELLANT DROP

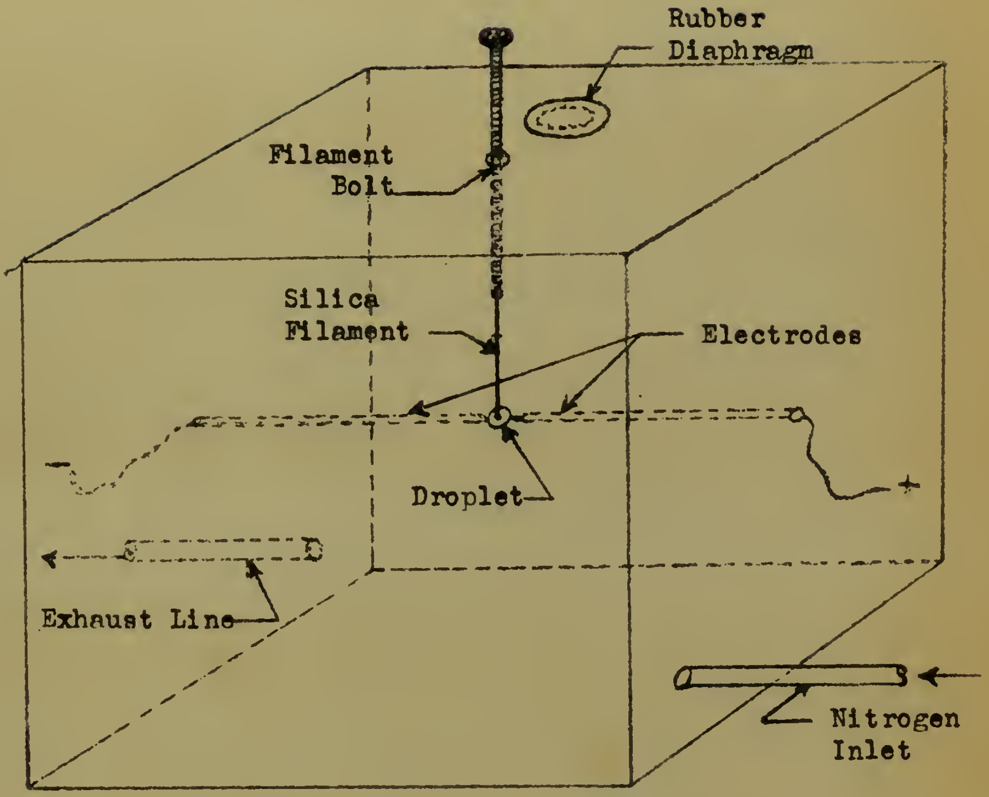


FIGURE 2. SKETCH OF APPARATUS FOR BURNING SINGLE DROPS IN NITROGEN

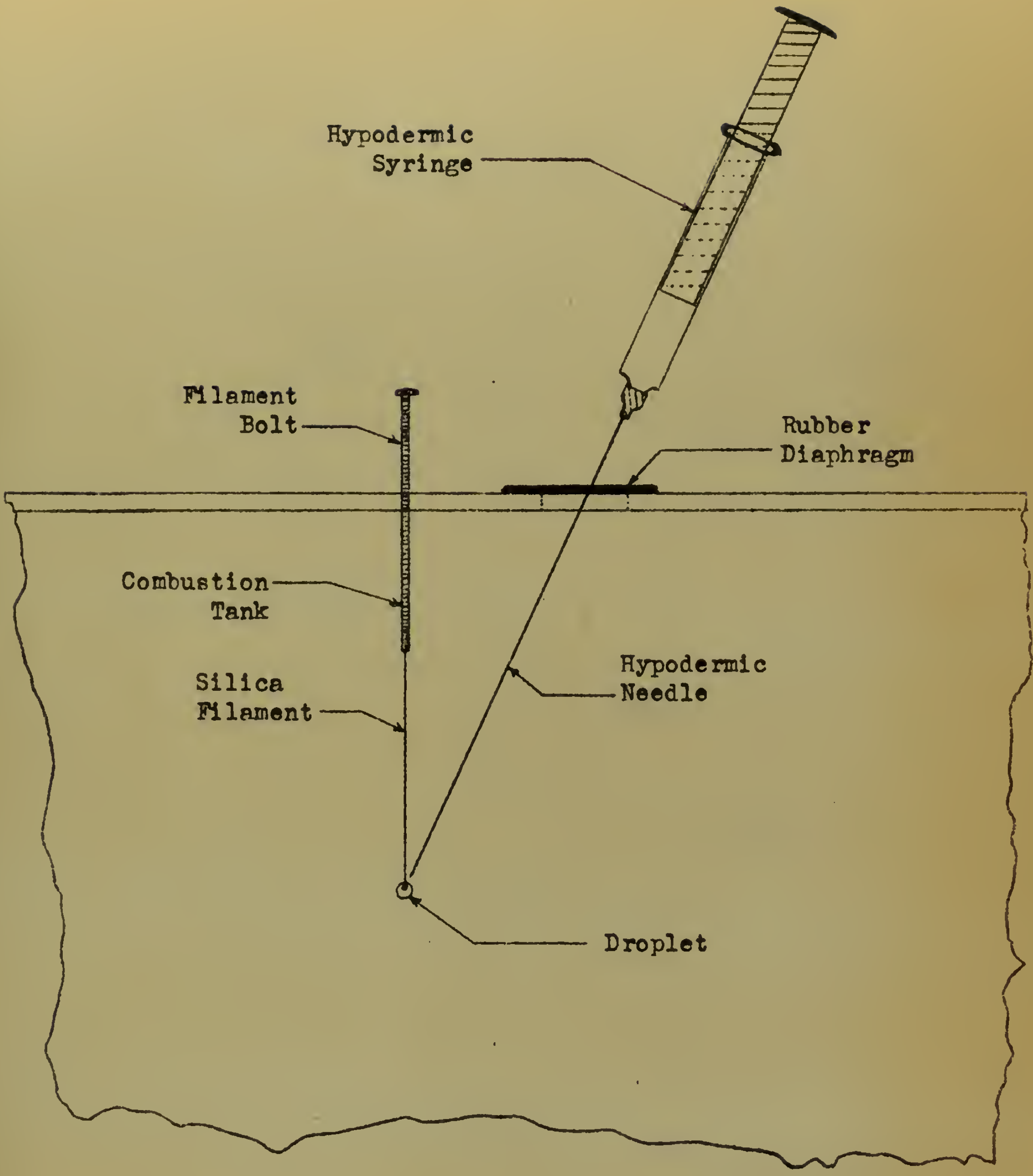


FIGURE 3. SKETCH OF APPARATUS FOR SUSPENDING DROP ON THE FILAMENT

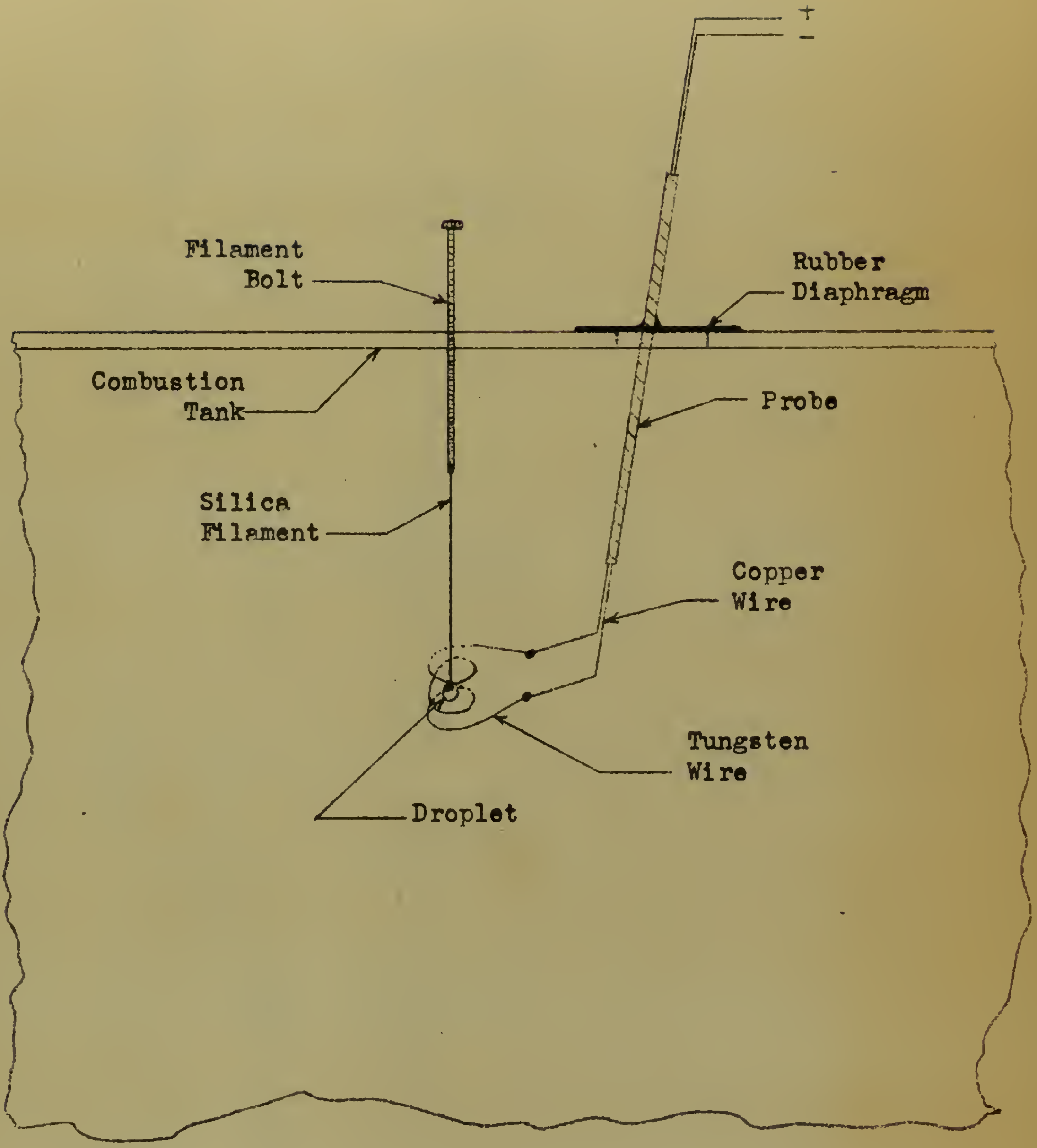


FIGURE 4. SKETCH OF APPARATUS FOR HOT WIRE IGNITION OF DROPLET

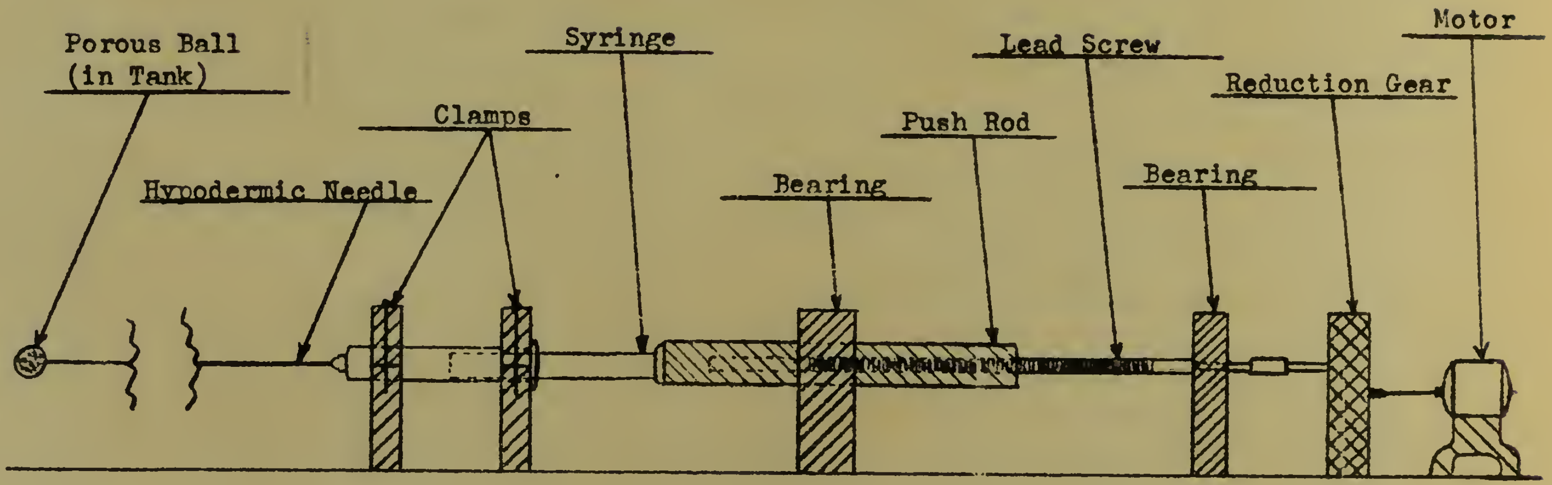


FIGURE 5. SKETCH OF APPARATUS FOR CONTINUOUSLY BURNING DROPS IN NITROGEN

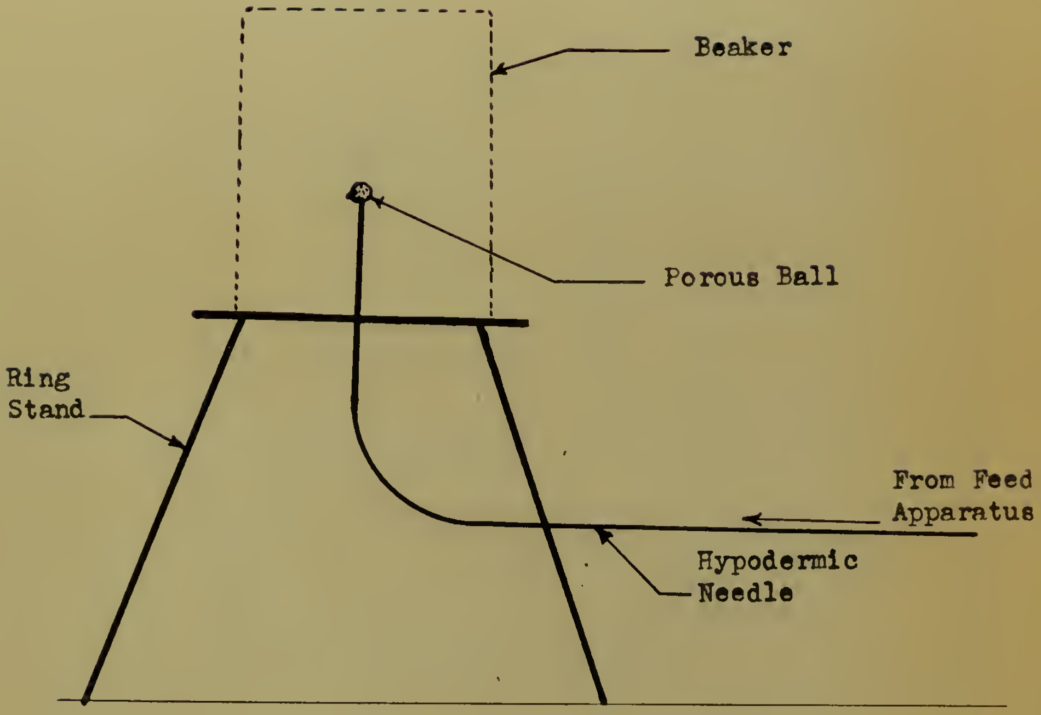


FIGURE 6. SKETCH OF APPARATUS FOR CONTINUOUSLY BURNING DROPS IN AIR

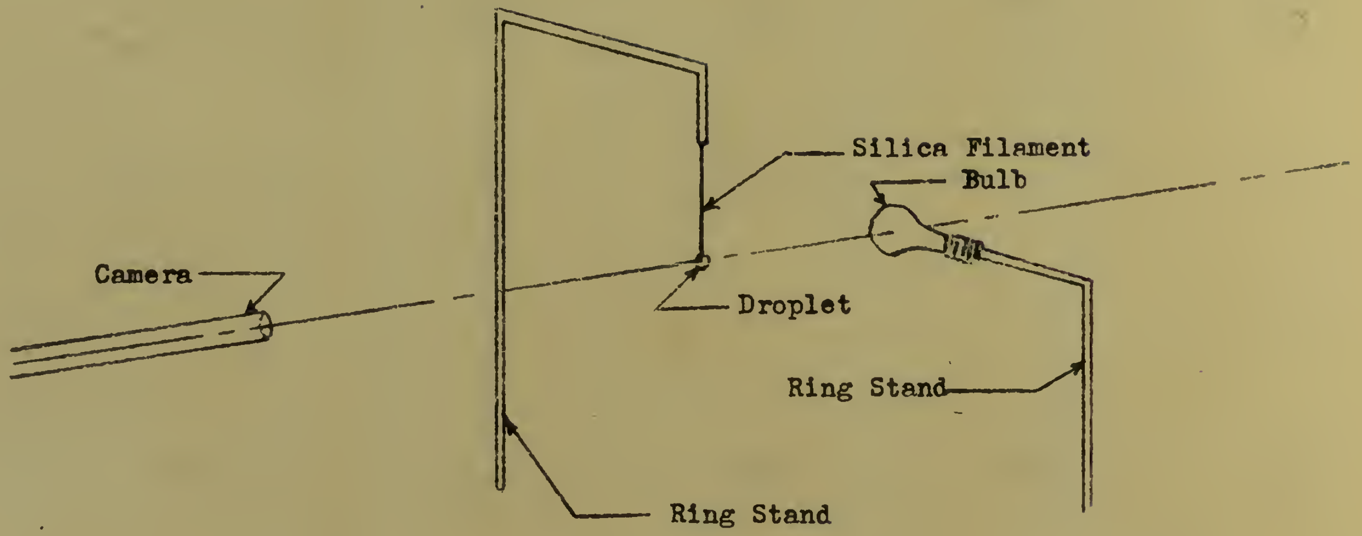
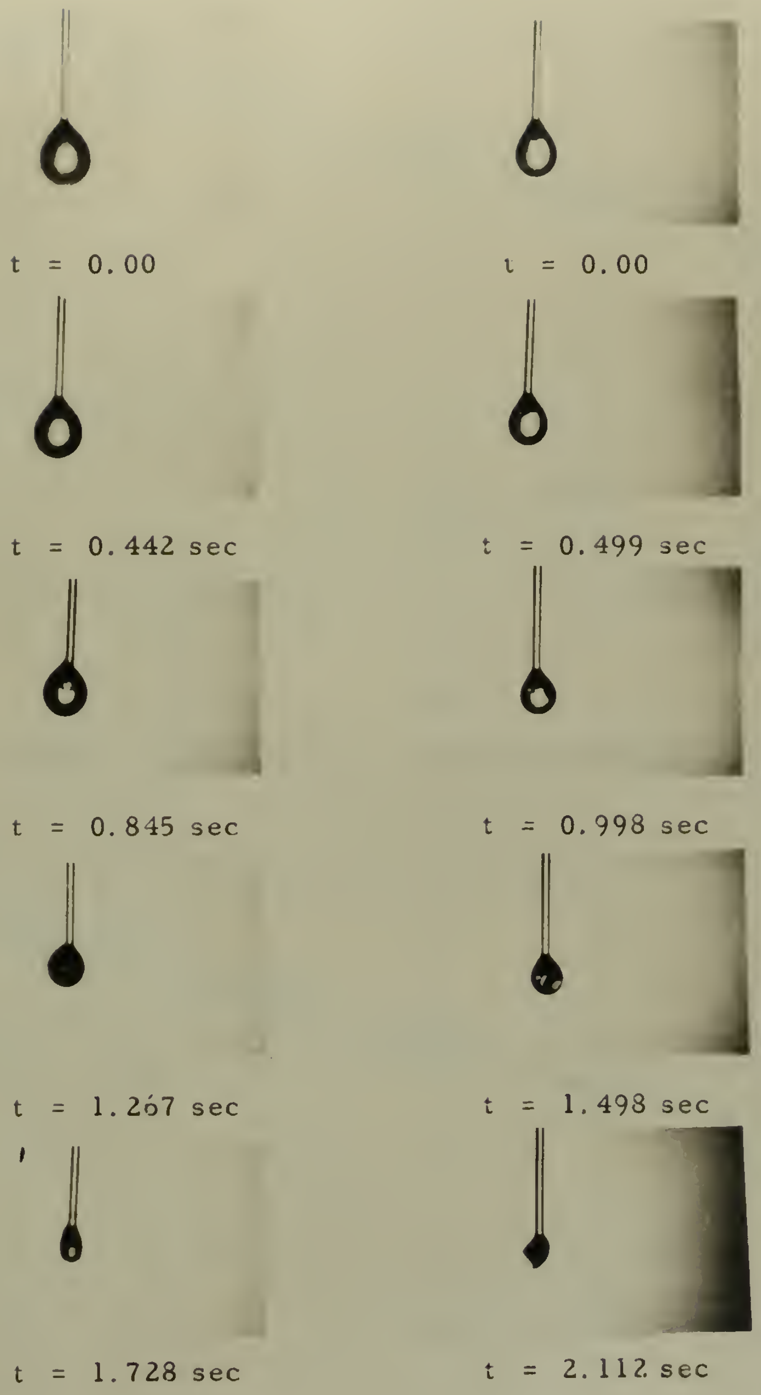


FIGURE 7. SKETCH OF APPARATUS FOR BURNING SINGLE DROPS IN AIR



8a. Hydrazine burning in air   8b. Nitromethane burning in air

FIGURE 8. PHOTOGRAPHS OF BURNING DROPS

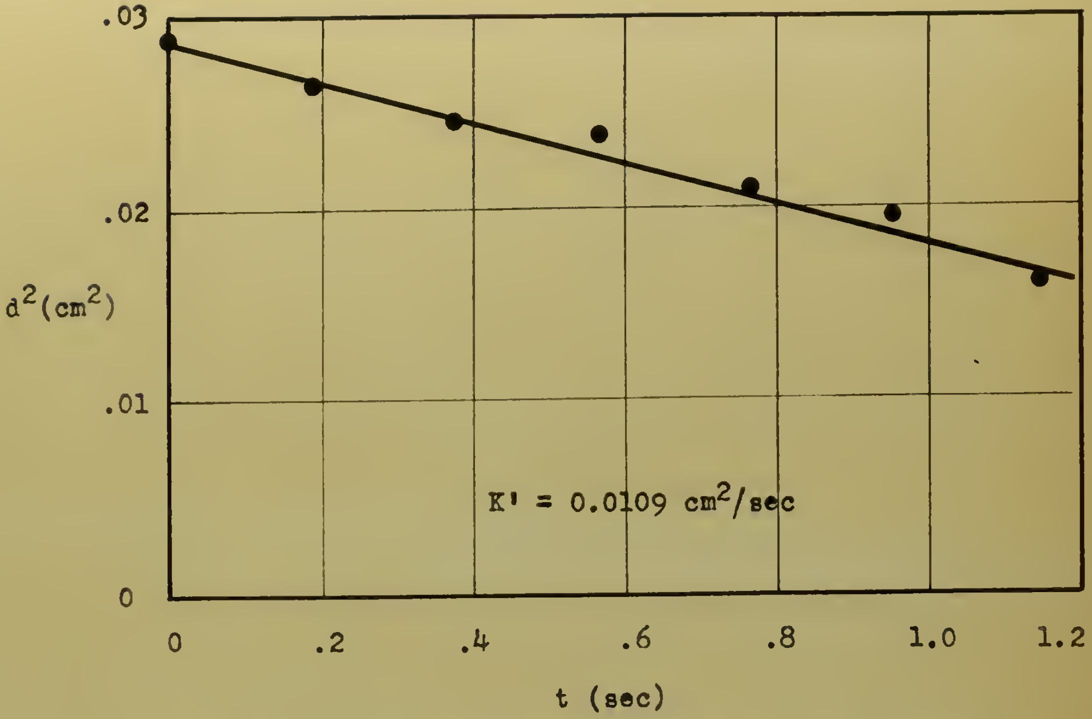


FIGURE 9. PLOT OF d^2 vs t FOR NITROMETHANE BURNING IN AIR

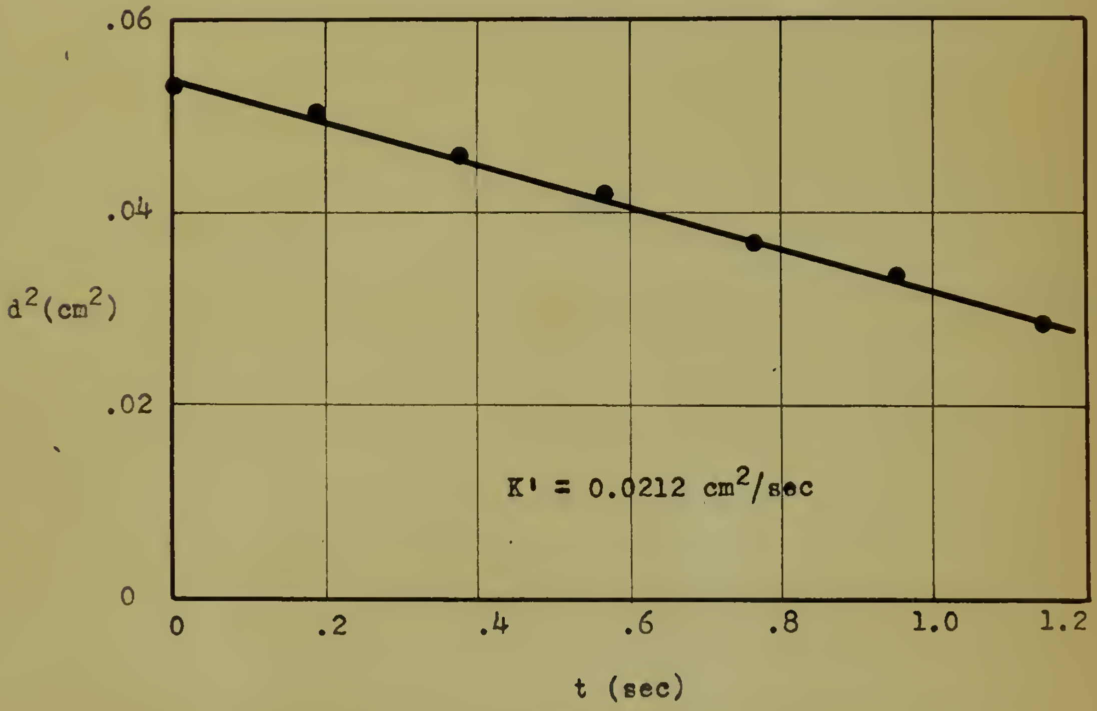


FIGURE 10. PLOT OF d^2 vs t FOR HYDRAZINE BURNING IN AIR

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On the burning of
single drops of mono-
propellants.

Thesis
K411 Kiley 23792
On the burning of single
drops of monopropellants.

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